

Fracture Testing of 2324-T39 Aluminum Alloy

D. S. Dawicke

Analytical Services and Materials, Inc.

ABSTRACT

Fracture tests were conducted on middle crack tension (M(T)) and compact tension (C(T)) specimens of 7.6mm-thick 2324-T39 aluminum in the L-T orientation. The configurations tested included 102mm-wide M(T), 305mm-wide M(T), 152mm-wide compact tension C(T), and 102mm-wide C(T) specimens. The measured critical crack-tip opening angle (CTOA) for the 102mm-wide M(T) tests, 305mm-wide M(T) tests, and 152mm-wide C(T) tests, after a small amount of crack extension, were 4.4° , 4.9° , and 5.1° respectively. The scatter involved with these measurements was about $\pm 1^\circ$.

NOMENCLATURE

a	crack length
W	specimen width
B	specimen thickness
S	applied stress
P	applied load
Δa	crack extension
COD	total crack opening displacement
PD	total pin displacement

INTRODUCTION

The critical crack-tip opening angle (CTOA) concept has been used successfully to predict the fracture behavior of thin-sheet aluminum alloys [1-6]. These studies have shown that for the thin-sheet aluminum alloy: the critical CTOA is

constant after an initial transient period [2], significant crack tunneling is present during the transient period [2], compact tension (C(T)) and middle crack tension (M(T)) fracture tests have the same critical CTOA [3], differences in the critical CTOA and fracture behavior were observed in different crack orientations (L-T and T-L) [4], the critical CTOA fracture criterion (obtained from small specimens) was able to predict the fracture behavior of larger specimens with and without multiple site damage (MSD) [5], and the critical CTOA during fracture is not constant through-the-thickness during the initial transient period, CTOA reaches a constant value [6].

An experimental fracture study was conducted on 7.6mm-thick, 2324-T39 aluminum alloy to assess the applicability of the CTOA criterion to thicker specimens. The configurations tested included C(T) and M(T) specimens. Measurements of load, crack extension, crack opening displacement and critical CTOA were made during the tests.

EXPERIMENTAL PROCEDURE

Fracture tests were conducted on M(T) and C(T) specimens of 7.6mm-thick 2324-T39 aluminum in the L-T orientation (i.e., the load was applied in the longitudinal or rolling direction and the crack was in the transverse direction or perpendicular to the longitudinal direction). The configurations tested included 102mm-wide M(T), 305mm-wide M(T), 152mm-wide compact tension C(T), and 102mm-wide C(T) specimens. Some of the 102mm-wide M(T) specimens had a 9.5mm-diameter hole in the center of the crack and the 102mm-wide C(T) specimens had a 10% side groove on each side. All specimens were fatigue precracked at loads that resulted in a final stress-intensity factor of about 8 MPa $\sqrt{\text{m}}$. The tests were conducted under displacement control and measurements of load, crack extension, and crack opening displacement were made as the crack grew. For the M(T) specimens, the center-line crack opening displacement was measured 10mm above and below the crack. For the C(T) specimens, the crack opening displacement was measured at the edge of the specimen, 10mm above and below the crack. The CTOA measurements were made using the optical microscopy (OM) technique [2].

Crack tunneling behavior was investigated with the 102mm-wide, side grooved C(T) specimens. The specimens were fatigue precracked, then loaded under displacement control until the crack began to stably tear. The loading was stopped and the specimen was fatigue cycled, until failure, at a stress ratio of $R=0.8$ and a maximum load that was 80% of the maximum load during the stable tearing portion of the test. The macroscopic and microscopic appearance of the stable tearing region was different than both the fatigue precracking and high- R fatigue regions. The interface between the regions denotes the crack front profile at the end of the fatigue precracking and the end of stable tearing.

EXPERIMENTAL RESULTS

A summary of the M(T) and C(T) fracture tests is given in Tables 1-4 and a tabular listing of all of the experimental measurements is given in Appendix A.

Fracture Results

The 102mm-wide M(T) fracture tests are summarized in Table 1. Two of the 102mm-wide M(T) specimens were supplied with a 9.5mm diameter center hole and a 8mm-long saw cut was made on both sides of the hole. Fatigue precracking was used to develop a sharp crack tip. Two additional M(T) specimens were machined from the fractured halves of the 305mm-wide M(T) specimens (these specimens did not have the center holes). The crack extension (measured on one side of the specimen) during fracture is plotted as a function of applied stress in Figure 1. Crack opening displacement measurements were made for tests MT4-03 and MT4-04, and plotted as a function of stress in Figure 2. The displacement measurements were made, on both sides, along the center line of the specimen and 10 mm above and below the crack plane. The values shown in Figure 2 are the average of the front and back displacement measurements.

The 305mm-wide M(T) fracture tests are summarized in Table 2. The crack extension (measured on one side of the specimen) during fracture is plotted as a function of applied stress in Figure 3. Crack opening displacement measurements were made and plotted as a function of stress in Figure 4. The

displacement measurements were made, on both sides, along the center line of the specimen and 10 mm above and below the crack plane. The values shown in Figure 4 are the average of the front and back displacement measurements. The crack opening displacement measurements were used to obtain crack length through the unloading compliance technique [7]. The compliance crack length measurements are shown along with the optical surface crack measurements in Figure 3. The compliance indicated crack extensions were greater than visual apparently because of crack tunneling.

The 152mm-wide C(T) fracture tests are summarized in Table 3. The crack extension (measured on one side of the specimen) during fracture is plotted as a function of applied load in Figure 5. The crack grew straight in only one test (CT6-02), in the other two tests the crack immediately turned and grew at an angle of about 45° to the plane of the fatigue precrack. Crack opening displacement measurements were made and plotted as a function of load in Figure 6. The displacement measurements were made on the edge of the specimen, 10 mm above and below the crack plane. Pin displacement (PD) were made and plotted as a function of load in Figure 7.

The 102mm-wide C(T) fractures tests are summarized in Table 4. These specimens had a 10% side groove, running along the crack plane, on both sides of the specimen. One specimen was loaded until failure and the other five were used to characterize crack tunneling. Crack opening displacement measurements were made and plotted as a function of load in Figure 8. The displacement measurements were made on the edge of the specimen, 10 mm above and below the crack plane. Pin displacement (or stroke) were made and are also plotted as a function of load in Figure 8.

CTOA Results

Critical crack tip opening angle (CTOA) measurements were made for the 102mm-wide M(T), 305mm-wide M(T), and 152mm-wide C(T) fracture tests. The CTOA measurements are reported in Tables 5-7 and plotted as a function of surface crack extension in Figure 9. The average CTOA values (after 2mm of surface crack extension) were 4.4° , 4.9° , and 5.1° for the 102mm-wide M(T),

305mm-wide M(T), and 152mm-wide C(T), respectively. The 102mm-wide M(T) fracture tests had a very small amount of stable tearing prior to specimen failure. This resulted in only a few CTOA measurements per test and making measurements difficult. The 305mm-wide M(T) and 152mm-wide C(T) had significantly more crack extension, thus more CTOA measurements.

SUMMARY

Fracture tests were conducted on M(T) and C(T) specimens of 7.6mm-thick 2324-T39 aluminum in the L-T orientation. The configurations tested included 102mm-wide M(T), 305mm-wide M(T), 152mm-wide compact tension C(T), and 102mm-wide C(T) specimens. Some of the 102mm-wide M(T) specimens had a 9.5mm-diameter hole in the center of the crack. The 102mm-wide C(T) specimens had a 10% side groove. The measured CTOA for the 305mm-wide M(T) tests and 152mm-wide C(T) tests were 4.9° and 5.1° , respectively. The scatter involved with these measurements was about $\pm 1^\circ$. The measured CTOA for the 102mm-wide M(T) tests was 4.4° , however, very little stable crack growth occurred before the specimen failed, making CTOA measurements difficult.

REFERENCES

- 1 Newman, J. C., Jr., Dawicke, D. S., and Bigelow, C. A., "Finite-Element Analyses and Fracture Simulation in Thin-Sheet Aluminum Alloy," NASA TM-107662, August 1992.
- 2 Dawicke, D. S. and Sutton, M. A., "Crack-Tip Opening Angle Measurements and Crack Tunneling Under Stable Tearing in a Thin Sheet 2024-T3 Aluminum Alloy, NASA-CR 191523, September 1993.
- 3 Dawicke, D. S., Sutton, M. A., Newman, J. C., Jr., and Bigelow, C. A., "Measurement and Analysis of Critical CTOA for an Aluminum Alloy Sheet," NASA TM-109024, September 1993.
- 4 Sutton, M. A., Dawicke, D. S., and Newman, J. C., Jr., "Orientation Effects on the Measurement and Analysis of Critical CTOA in an Aluminum Alloy Sheet," NASA TM-109153, September 1994.

- 5 Dawicke, D. S., Newman, J. C., Jr., Sutton, M. A., and Amstutz, B. E., "Stable Tearing Behavior of a Thin-Sheet Material with Multiple Cracks," NASA TM-109131, June 1994.
- 6 Dawicke, D. S., Newman, J. C., Jr., and Bigelow, C. A., "Three-Dimensional CTOA and Constraint Effects During Stable Tearing in a Thin-Sheet Material," NASA TM-109183, February 1995.
- 7 "1994 Annual Book of ASTM Standards, Section 3: Metal Test Methods and Analytical Procedures," ASTM PCN 01-030191-23, p. E647.

Table 1
Summary of the 102mm-wide M(T) Fracture Tests

ID	Crack Length, a (mm)	Max Stress, S (MPa)	Comments
MT4-03	29.7	264.9	9.5mm center hole
MT4-04	30.2	256.8	9.5mm center hole
MT4-05	33.0	273.2	Cut from MT12-01, crack tunneling test
MT4-06	33.0	277.5	Cut from MT12-02

Table 2
Summary of the 305mm-wide M(T) Fracture Tests

ID	Crack Length, a (mm)	Max Stress, S (MPa)	Comments
MT12-01	114.3	205.3	
MT12-02	119.4	203.4	

Table 3
Summary of the 152mm-wide C(T) Fracture Tests

ID	Crack Length, a (mm)	Max Load, P (KN)	Comments
CT6-01	64.6	32.2	Crack turned and grew at 45°
CT6-02	62.0	29.8	Crack grew straight
CT6-03	64.9	34.2	Crack turned and grew at 45°

Table 4
Summary of the 102mm-wide Side-Grooved C(T) Fracture Tests

ID	Crack Length, a (mm)	Max Load, P (KN)	Comments
CT4-01	40.6	15.6	only compliance crack length measurements
CT4-02	41.9	12.0	crack tunneling test (limited stable tearing)
CT4-03	41.5	15.6	crack tunneling test (limited stable tearing)
CT4-04	41.7	14.4	crack tunneling test (limited stable tearing)
CT4-05	41.8	14.0	crack tunneling test (limited stable tearing)
CT4-06	40.8	14.7	crack tunneling test (limited stable tearing)

Table 5
CTOA Measurements for the 102mm-wide M(T) Fracture Tests

Crack Extension, Δa (mm)	CTOD (degree)
0.02	6.9
0.38	6.3
0.74	4.9
1.09	4.6
1.40	4.6
2.41	3.3
2.67	3.8
3.25	4.3
3.40	4.9
5.05	4.4
5.11	4.4

Table 6
CTOA Measurements for the 305mm-wide M(T) Fracture Tests

Crack Extension, Δa (mm)	CTOD (degree)
0.25	11.5
0.51	11.4
0.64	11.3
1.68	6.2
2.26	5.3
3.30	3.8
3.68	4.2
4.32	4.7
4.83	4.5
5.66	5.0
7.11	5.2
7.87	5.5
7.92	5.6
9.96	4.6
12.27	4.5
13.28	4.7
15.19	5.1
15.75	5.1
16.26	5.3

Table 7
CTOA Measurements for the 152mm-wide C(T) Fracture Tests

Crack Extension, Δa (mm)	CTOD (degree)
0.33	8.4
0.66	8.6
1.52	6.6
4.32	5.9
6.43	5.4
7.92	4.7
9.07	4.8
10.52	5.4
12.04	3.7
15.42	5.7
17.83	5.8
23.88	4.4
39.47	5.1
43.43	5.3

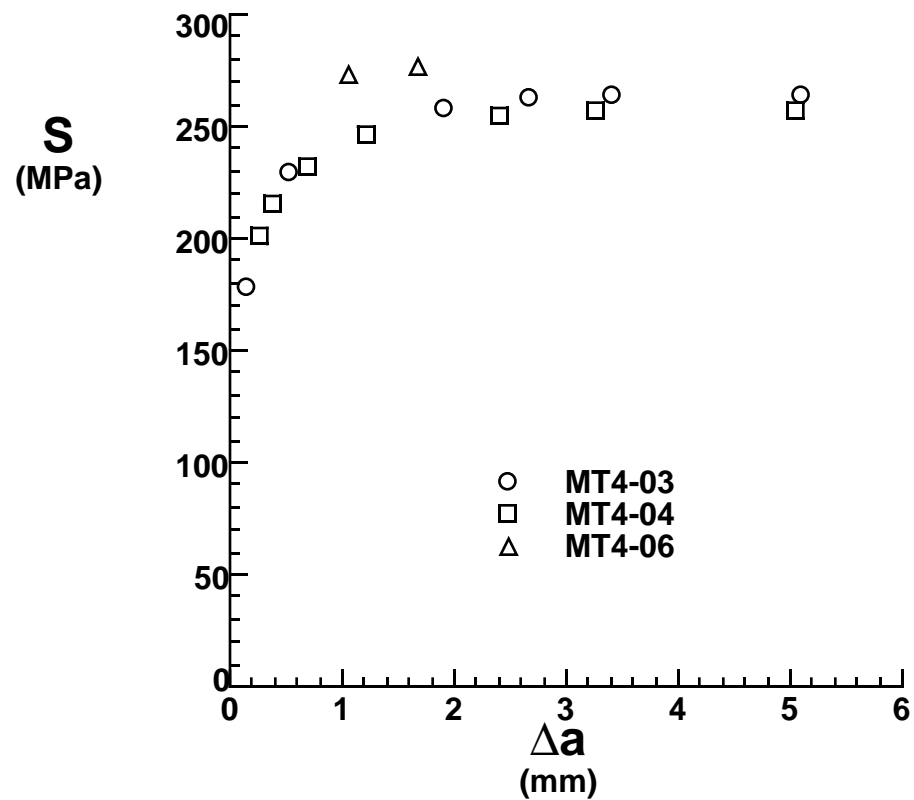


Figure 1 Crack extension data for the 102mm-wide M(T) fracture tests.

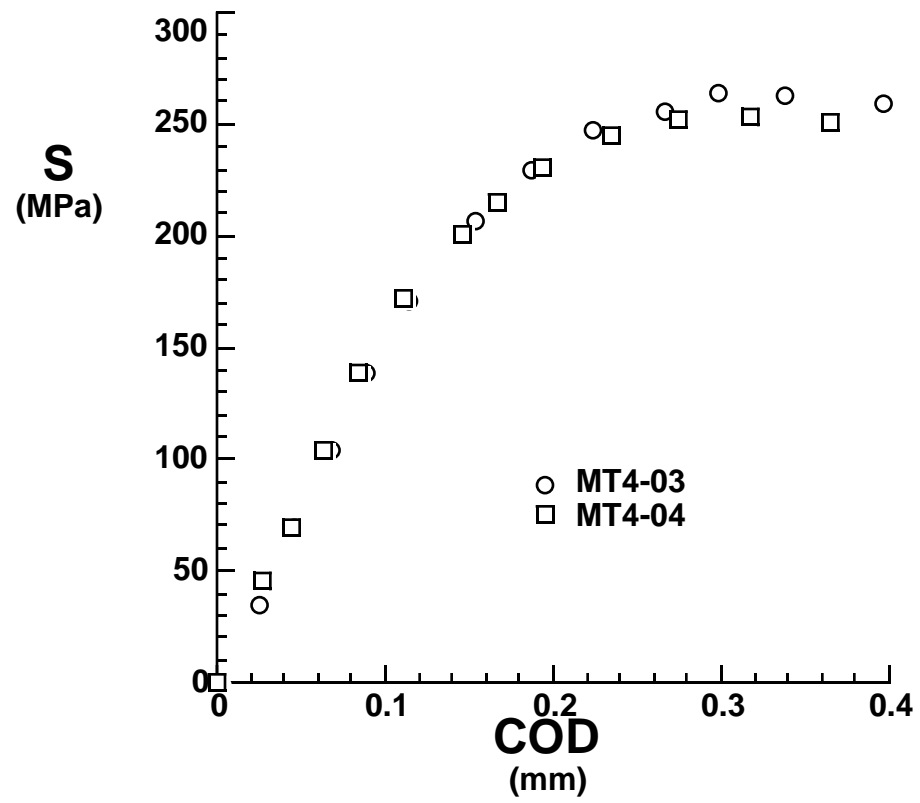


Figure 2 Crack opening displacement measurements for the 102mm-wide M(T) fracture tests.

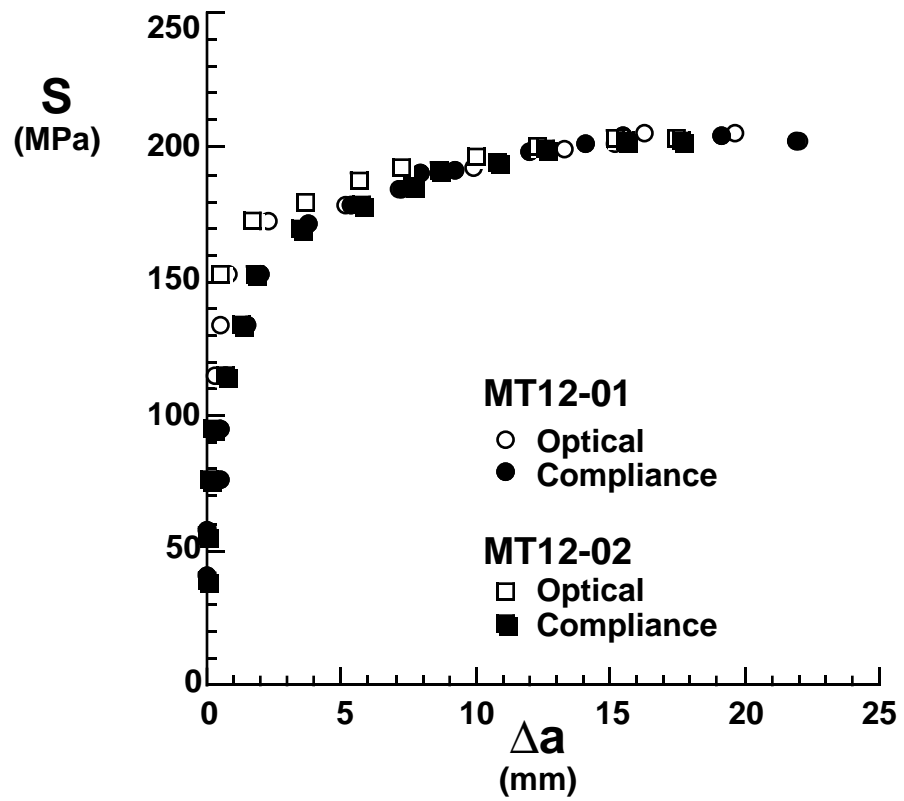


Figure 3 Crack extension data for the 305mm-wide M(T) fracture tests.

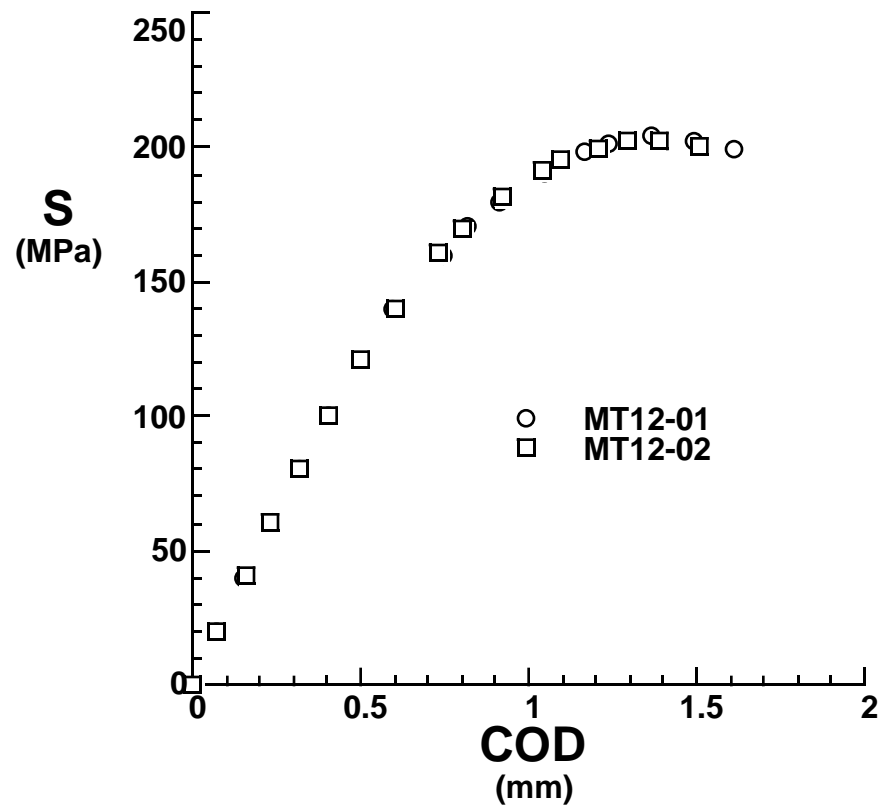


Figure 4 Crack opening displacement measurements for the 305mm-wide M(T) fracture tests.

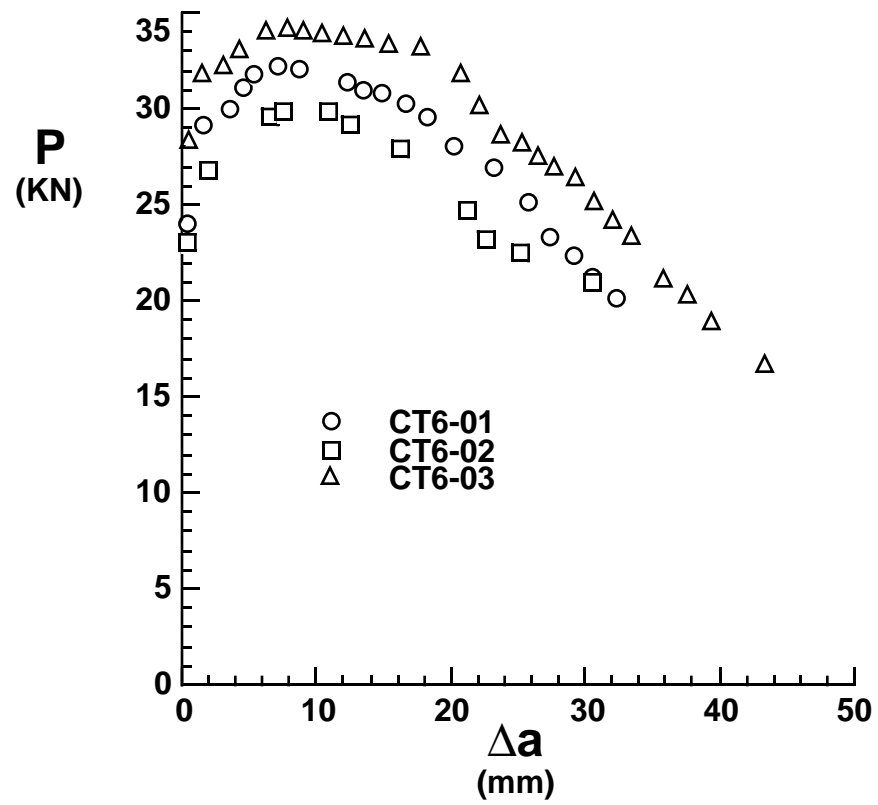


Figure 5 Crack extension data for the 152mm-wide C(T) fracture tests.

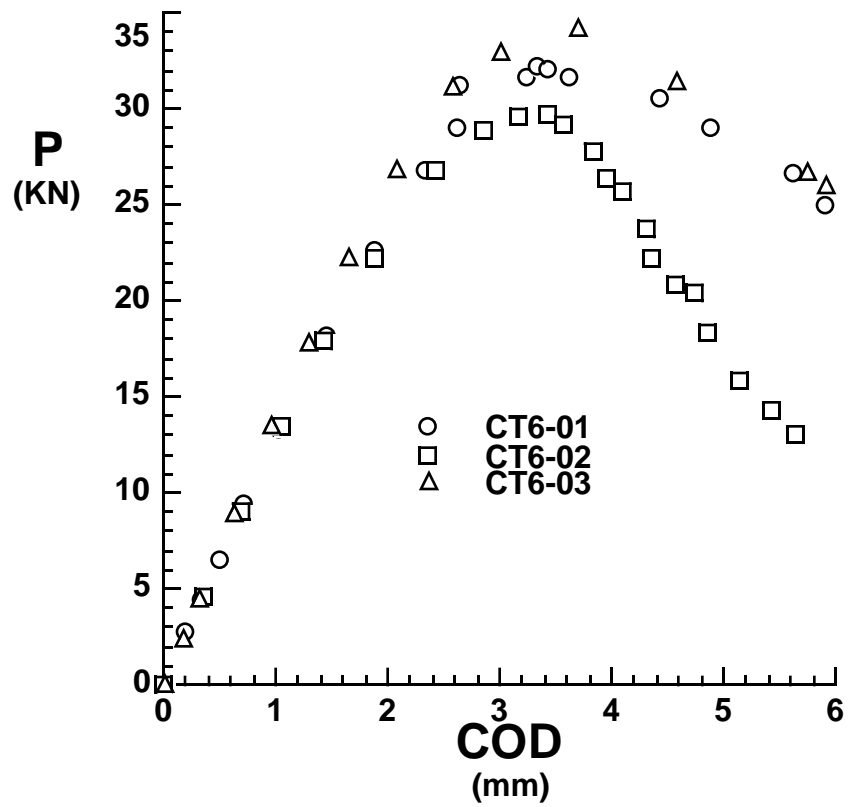


Figure 6 Crack opening displacements measurements for the 152mm-wide C(T) fracture tests.

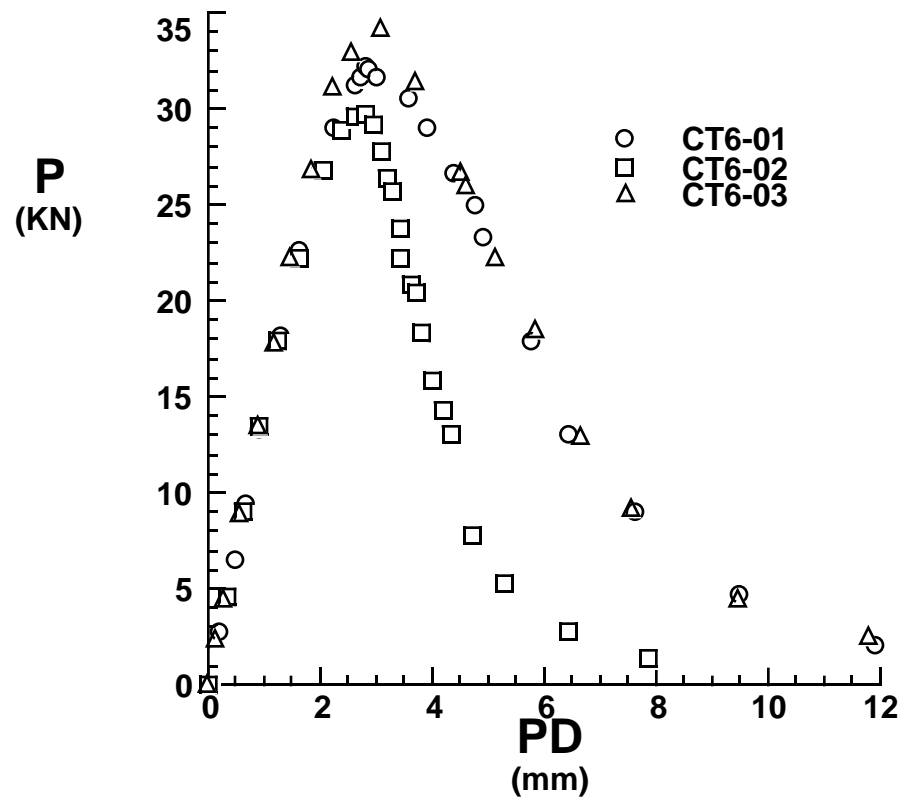


Figure 7 Pin displacement (or stroke) measurements for the 152mm-wide C(T) fracture tests.

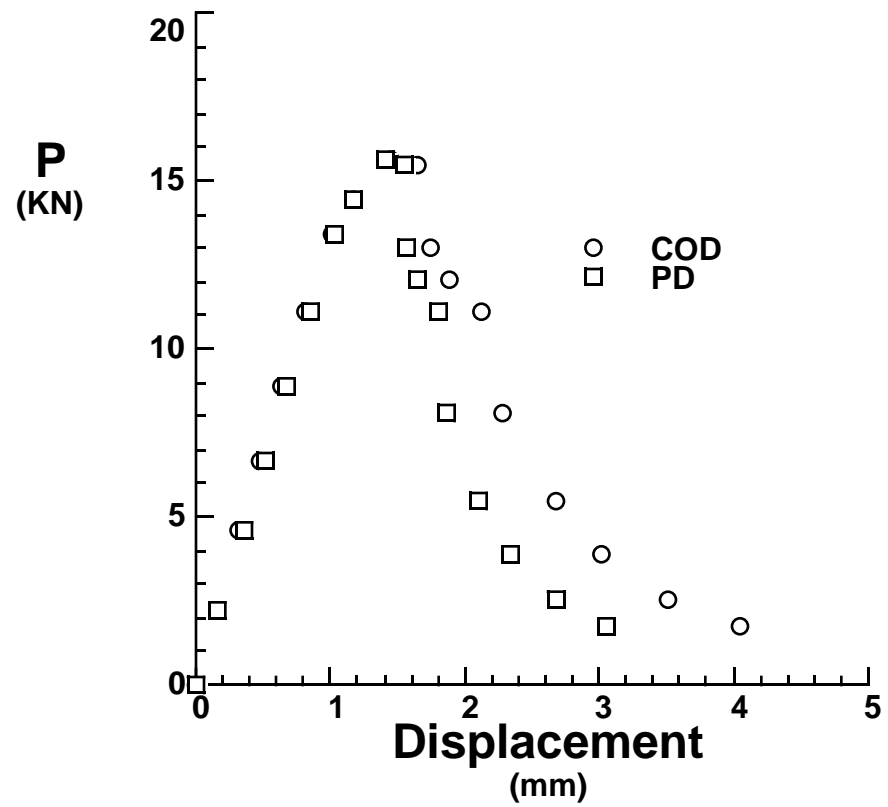


Figure 8 Crack opening and pin displacement measurements for the 102mm-wide (side groove) C(T) fracture tests.

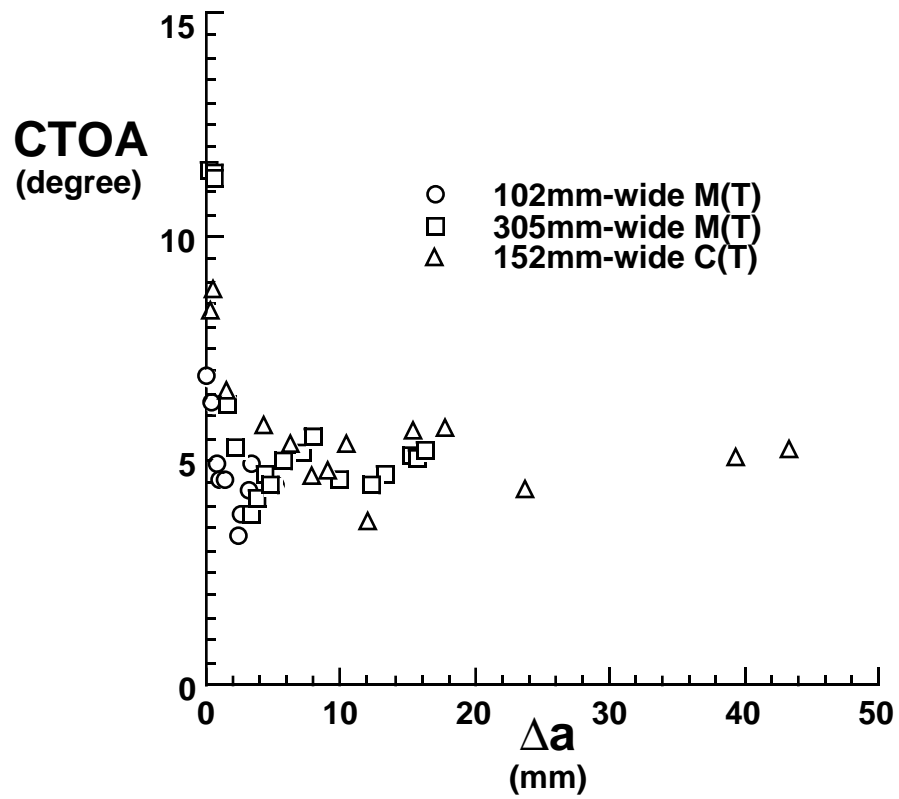


Figure 9 Critical crack tip opening angle (CTOA) measurements for the 102mm-wide M(T), 305mm-wide M(T), and 152mm-wide C(T) fracture tests.

APPENDIX A
Test Data Summary

Table 1
Crack Extension Data for Test MT4-03

Crack Extension, Δa (mm)	Stress, S (MPa)
0.00	0.0
0.15	178.1
0.53	229.8
1.91	258.0
2.66	262.6
3.40	264.9
5.11	264.3

Table 2
Crack Opening Displacement Data for Test MT4-03

COD (mm)	Stress, S (MPa)
0.0	0.0
0.025	35.0
0.046	69.2
0.068	103.6
0.088	138.2
0.114	171.0
0.154	207.0
0.187	229.6
0.224	247.8
0.266	255.8
0.298	263.3
0.338	263.3
0.397	259.4

Table 3
Crack Extension Data for Test MT4-04

Crack Extension, Δa (mm)	Stress, S (MPa)
0.00	0.0
0.25	201.1
0.38	216.0
0.69	232.1
1.22	245.9
2.41	255.1
3.25	256.8
5.05	256.8

Table 4
Crack Opening Displacement Data for Test MT4-04

COD (mm)	Stress, S (MPa)
0.0	0.0
0.026	45.9
0.045	69.1
0.064	103.6
0.084	138.1
0.112	172.1
0.146	200.3
0.167	215.1
0.193	230.3
0.235	244.6
0.275	251.7
0.317	252.9
0.366	251.4

Table 5
Crack Extension Data for Test MT4-06

Crack Extension, Δa (mm)	Stress, S (MPa)
0.00	0.0
1.04	274.1
1.68	277.5

Table 6
Crack Extension Data for Test MT12-01

Crack Extension, Δa (mm)	Stress, S (MPa)
0.00	0.0
0.25	114.9
0.51	134.1
0.79	153.2
2.26	172.4
5.16	178.9
7.11	184.8
7.92	190.6
9.96	192.7
13.3	199.6
15.2	201.9
16.3	204.9
19.7	205.3
22.0	202.6

Table 7
Crack Opening Displacement Data for Test MT12-01

COD (mm)	Stress, S (MPa)
0.000	0.0
0.073	20.1
0.152	40.0
0.235	60.4
0.316	80.1
0.403	100.3
0.497	120.0
0.599	140.2
0.746	160.1
0.817	170.2
0.914	180.1
1.049	190.2
1.165	198.9
1.235	201.2
1.368	204.7
1.493	201.9
1.610	199.3

Table 8
Compliance Crack Extension Data for Test MT12-01

Crack Extension, Δa (mm)	Stress, S (MPa)
0.00	40.5
0.02	57.4
0.49	76.5
0.49	95.6
0.68	114.6
1.46	133.8
1.98	152.8
3.73	171.5
5.36	178.4
7.29	184.3
7.98	190.1
9.20	191.4
11.99	198.9
14.12	201.2
15.45	204.5
19.18	204.7
21.94	201.9

Table 9
Crack Extension Data for Test MT12-02

Crack Extension, Δa (mm)	Stress, S (MPa)
0.00	0.0
0.51	153.2
1.68	172.4
3.68	179.7
5.66	187.9
7.26	192.5
10.0	196.7
12.3	200.9
15.1	203.4
17.5	203.2

Table 10
Compliance Crack Extension Data for Test MT12-02

Crack Extension, Δa (mm)	Stress, S (MPa)
0.00	38.3
0.03	55.9
0.11	76.6
0.21	95.8
0.71	114.9
1.29	133.7
1.82	153.0
3.47	169.2
5.80	178.7
7.63	185.5
8.63	191.7
10.86	194.8
12.60	199.2
15.56	202.4
17.71	202.3

Table 11
Crack Opening Displacement Data for Test MT12-02

COD (mm)	Stress, S (MPa)
0.000	0.0
0.071	20.0
0.155	41.1
0.234	60.5
0.318	80.9
0.402	100.1
0.501	120.9
0.600	140.3
0.734	160.7
0.804	170.1
0.919	181.6
1.037	191.2
1.100	195.8
1.209	199.6
1.290	202.4
1.388	202.3
1.508	200.7

Table 12
Crack Extension Data for Test CT6-01

Crack Extension, Δa (mm)	Load, P (KN)
0.00	0.0
0.46	24.1
1.68	29.1
3.51	29.9
4.57	31.1
5.41	31.8
7.14	32.2
8.81	32.1
12.34	31.4
13.49	31.0
14.94	30.8
16.71	30.2
18.31	29.5
20.30	28.1
23.32	26.9
25.83	25.1
27.41	23.4
29.11	22.3
30.61	21.2
32.44	20.1

Table 13
Crack Opening Displacement Data for Test CT6-01

COD (mm)	PD (mm)	Load, P (KN)
0.000	0.000	0.0
0.203	0.190	2.7
0.338	0.313	4.5
0.497	0.455	6.6
0.717	0.649	9.4
1.028	0.922	13.4
1.443	1.276	18.2
1.870	1.632	22.7
2.327	2.007	26.9
2.616	2.238	29.1
3.130	2.634	31.2
3.249	2.725	31.7
3.327	2.788	32.2

Table 13 (cont.)
Crack Opening Displacement Data for Test CT6-01

COD (mm)	PD (mm)	Load, P (KN)
3.431	2.861	32.1
3.621	2.995	31.7
4.427	3.579	30.5
4.885	3.894	29.0
5.608	4.400	26.7
5.907	4.787	24.9
	4.901	23.4
	5.748	17.9
	6.449	13.1
	7.641	9.0
	9.458	4.7
	11.886	2.1

Table 14
Crack Extension Data for Test CT6-02

Crack Extension, Δa (mm)	Load, P (KN)
0.00	0.0
0.46	23.0
2.03	26.8
6.55	29.6
7.65	29.8
11.00	29.8
12.57	29.2
16.36	28.0
21.18	24.7
22.68	23.1
25.12	22.5
30.48	21.0

Table 15
Crack Opening Displacement Data for Test CT6-02

COD (mm)	PD (mm)	Load, P (KN)
0.000	0.000	0.0
0.351	0.313	4.5
0.700	0.621	9.1
1.045	0.921	13.4
1.434	1.252	17.9
1.890	1.629	22.3
2.437	2.072	26.8
2.857	2.401	29.0
3.160	2.627	29.6
3.426	2.824	29.7
3.582	2.934	29.2
3.832	3.108	27.8
3.959	3.190	26.4
4.094	3.285	25.7
4.306	3.427	23.8
4.353	3.449	22.2
4.573	3.601	20.8
4.731	3.716	20.5
4.861	3.796	18.3
5.149	3.993	15.8
5.426	4.187	14.3
5.642	4.342	13.1
	4.703	7.8
	5.298	5.3
	6.407	2.8
	7.858	1.4

Table 16
Crack Extension Data for Test CT6-03

Crack Extension, Δa (mm)	Load, P (KN)
0.00	0.0
0.66	28.3
1.52	31.8
3.12	32.3
4.32	33.1
6.43	34.1
7.92	31.2

Table 16 (cont.)
Crack Extension Data for Test CT6-03

Crack Extension, Δa (mm)	Load, P (KN)
9.07	34.0
10.52	33.9
12.04	33.8
13.74	33.6
15.42	33.3
17.83	33.2
20.80	31.8
22.28	30.1
23.88	28.6
25.35	28.2
26.59	27.5
27.84	26.9
29.44	26.3
30.81	25.1
32.21	24.2
33.53	23.4
36.00	21.1
37.77	20.3
39.47	18.9
43.43	16.7

Table 17
Crack Opening Displacement Data for Test CT6-03

COD (mm)	PD (mm)	Load, P (KN)
0.000	0.000	0.0
0.157	0.158	2.4
0.307	0.300	4.5
0.619	0.586	8.9
0.953	0.883	13.5
1.278	1.169	17.8
1.655	1.491	22.3
2.073	1.843	26.8
2.567	2.252	31.1
3.005	2.594	32.9
3.692	3.096	34.2
4.574	3.717	31.4

Table 17 (cont.)
Crack Opening Displacement Data for Test CT6-03

COD (mm)	PD (mm)	Load, P (KN)
5.735	4.524	26.7
5.904	4.641	26.0
	5.148	22.3
	5.863	18.5
	6.678	12.9
	7.564	9.2
	9.484	4.4
	11.801	2.4

Table 18
Crack Opening Displacement Data for Test CT4-01

COD (mm)	PD (mm)	Load, P (KN)
0.000	0.000	0.0
0.160	0.167	2.2
0.327	0.348	4.6
0.479	0.508	6.7
0.643	0.676	8.9
0.814	0.851	11.1
1.011	1.041	13.4
1.173	1.181	14.5
1.448	1.404	15.6
1.650	1.547	15.5
1.755	1.573	13.0
1.881	1.646	12.0
2.133	1.810	11.1
2.287	1.865	8.1
2.671	2.099	5.5
3.024	2.333	3.9
3.512	2.672	2.5